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QUARKONIA PRODUCTION AT THE TEVATRON

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Abstract

Charmonium and bottomonium production has been studied using $\mu^+\mu^-$ data samples collected by the CDF and D0 experiments during the 1992-96 $p\overline{p}$ collider run at the Fermilab Tevatron. Differential cross sections as a function of the transverse momentum of the reconstructed quarkonium states have been measured. The results are compared with QCD calculations which take into account different quarkonium production mechanisms.

1 Introduction

Charmonium and bottomonium production rates have been measured using dimuon data samples collected by the CDF and D0 experiments during the 1992-96 $p\overline{p}$ collider run at the Fermilab Tevatron. During this run, CDF and D0 respectively collected 110 pb^{-1} and 60 pb^{-1} of integrated luminosity from dimuon triggers. Differential cross sections for the J/ψ, ψ(2S) and the Υ(1S), Υ(2S), and Υ(3S) states have been measured using their $\mu^+\mu^-$ decay channels.

Initial CDF measurements of J/ψ and ψ(2S) production rates during the 1988-89 collider run showed production cross sections considerably larger than the contemporary QCD models predicted [1].

In these early studies, the dominant processes for ψ production were assumed to be $b\overline{b}$ pair creation followed by the decay $B \rightarrow \psi X$ and prompt production via parton (gluon-gluon) fusion directly into a color singlet $c\overline{c}$ state. In the case of the J/ψ and the Υ states, the radiative decays of χ_c and χ_b mesons were thought to be the dominant prompt production mechanisms. It has since been pointed out that in addition to gluon fusion in the color singlet model, intermediate color octet states and gluon fragmentation processes should also be important direct sources of prompt quarkonium production [2].

Both CDF and D0 have applied various methods to disentangle the different sources of quarkonia production (direct production, χ decay, and b decay) allowing for a more precise testing of the different theoretical models which are thought to contribute to the total inclusive quarkonia production cross sections.

2 Charmonium Total Cross Sections

In the CDF analyses, both muons of a reconstructed ψ candidate are required to have $|\eta| < 0.6$ and $p_T > 2.0$ GeV/c with at least one muon of the pair having $p_T > 2.8$ GeV/c. The reconstructed J/ψ or ψ(2S) candidates must have $p_T > 5.0$ GeV/c. About 22,000 J/ψ events and 800 ψ(2S) events are reconstructed in data samples of 15.4 pb^{-1} and 17.8 pb^{-1} respectively. CDF measures the product of the dimuon branching ratio times the integrated cross section to be $17.4 \pm 0.1^{+2.6}_{-2.8}$ nb for J/ψ and $0.57 \pm 0.04^{+0.08}_{-0.09}$ nb for ψ(2S).

In the D0 analysis, muons with transverse momentum greater than 3 GeV/c are reconstructed in the central ($|\eta| < 0.6$) [4] and forward ($2.5 < |\eta| < 3.7$) [5] pseudorapidity regions where the dimuon candidates are required to have $p_T > 1$ GeV/c. About 4,000 J/ψ events in the central and about 500 events in the forward rapidity ranges are found from a fit to a Gaussian function and physics-motivated background in samples of 60 pb^{-1} and 9.3 pb^{-1} respectively. The D0 tracking momentum resolution is such that it does not allow separation of the J/ψ and ψ(2S) states. D0 measures the product of the dimuon branching ratio times the integrated cross section to be $2.08 \pm 0.17 \pm 0.46$ nb for J/ψ in the central region and $0.40 \pm 0.04 \pm 0.04$ nb in the forward region for $p_T(J/\psi) > 8.0$ GeV/c.

3 Charmonium from b Decay

The CDF collaboration, using a silicon vertex detector, separates the J/ψ and $\psi(2S)$ samples into components arising from b decay and from prompt production by analyzing the proper decay-length ($c\tau$) distributions. The $c\tau$ distribution is fit to three components: an exponential convoluted with a Gaussian resolution function for the b hadron decay contribution, a Gaussian function centered at zero for prompt production, and a Gaussian function with positive and negative exponential tails to describe the background, both combinatorial as well as from sequential $b \to \mu^- c \to \mu^+ s$ decays. The samples are divided into bins of $p_T(\mu^+\mu^-)$ and fit separately for each range. The resulting b fractions are then convoluted with the inclusive differential ψ cross sections to give the b decay cross sections shown in figure 1. The results are within a factor of 3-4 of the NLO QCD prediction [3] and are consistent with other b cross section results from the Tevatron.

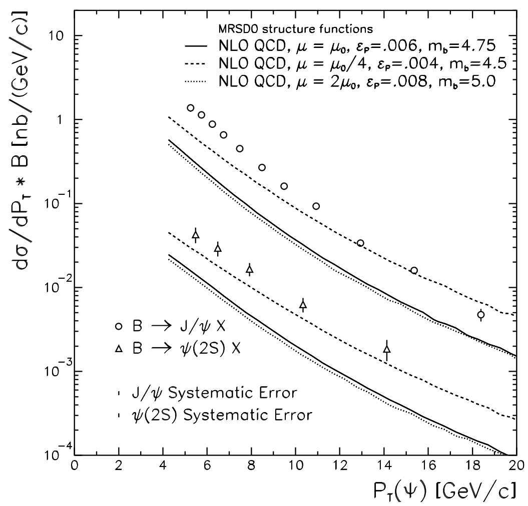

Figure 1: J/ψ and $\psi(2S)$ cross sections from b hadron decay vs. $p_T(\psi)$.

4 Direct Charmonium Production

Once the b decay component is removed, what is left is the differential ψ cross sections due to prompt production mechanisms.

All prompt $\psi(2S)$ are believed to be directly produced since χ_c states with sufficient mass to decay to $\psi(2S)$ lie above the threshold for strong decays to $D\overline{D}$ meson pairs. On the other hand, prompt J/ψ are produced not only directly but also via χ_c radiative decays.

CDF has determined the fraction of the prompt J/ψ sample coming from χ_c decay by fully reconstructing the decay $\chi_c \to J/\psi\gamma$. Photon candidates which are detected in the central electromagnetic calorimeter with energy greater than 1 GeV and having no charged track pointing to the calorimeter tower are combined with $\mu^+\mu^-$ pairs consistent with the J/ψ mass. A peak containing 1230 ± 72 χ_c candidates is observed in the mass difference distribution $M(\mu^+\mu^-\gamma) - M(\mu^+\mu^-)$. The background under the peak is modelled by embedding simulated π^0 and η^0 decay photons in real J/ψ events. The fraction of J/ψ events coming from prompt χ_c decay, measured in 4 different p_T bins, ranges from about 32% in the 4-6 GeV/c bin to 28% in the bin $p_T > 10$ GeV/c. The D0 measurement of this fraction is consistent with these results [4].

By multiplying the prompt J/ψ cross section by the χ_c fractions described above, CDF extracts the differential J/ψ production cross section due to prompt χ_c deacy and consequently the direct J/ψ production cross section. The measured rate of prompt J/ψ production from χ_c decay is a factor ~ 3 higher than the lowest order QCD prediction.

The differential cross sections for *direct* J/ψ and ψ(2S) production are shown in figure 2. The rate of direct J/ψ and ψ(2S) production is a factor of 50 larger than predictions based on the color singlet model of bound $c\bar{c}$ states [6]. The color singlet prediction, shown as the dotted line in figure 2, not only underestimates the magnitude of the measured cross sections but also incorrectly describes the shape of the p_T distribution.

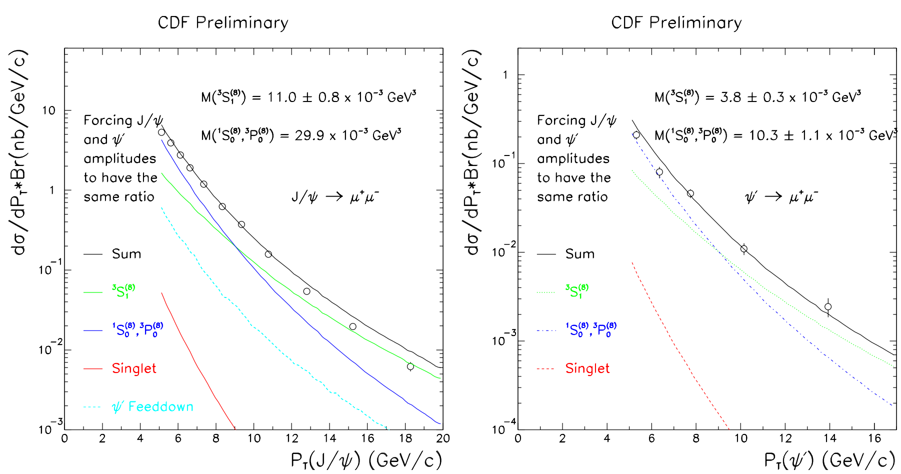

Figure 2: Direct J/ψ (left) and ψ(2S) (right) cross sections as a function of $p_T(\psi)$.

One proposal to explain the observed direct charmonium production rates is to include $c\bar{c}$ pairs produced in a color-octet state [2]. The initial production can be calculated perturbatively and can be used to predict the p_T dependence of the cross sections. The transition to a color-singlet state during the formation of a bound $c\bar{c}$ pair proceeds via soft gluon emission. This latter process cannot be calculated perturbatively, so the normalization is found by fitting the theory to the data. Figure 2 shows that the direct J/ψ and ψ(2S) cross sections can be described quite well when the color-octet contributions are included [7]. This model can be further tested by applying the parameters from these fits to predictions for photoproduction and fixed target hadroproduction experiments and by measuring the ψ(2S) polarization in $p\overline{p}$ collisions.

5 Forward Charmonium Production

The D0 collaboration has made the first measurement of the differential cross section $d\sigma/dp_T$ for J/ψ production in the forward pseudorapidity region as shown in figure 3. Figure 3 also shows the differential cross section $d\sigma/d\eta$. Both cross sections are measured for $p_T(J/\psi) >$ 8 GeV/c.

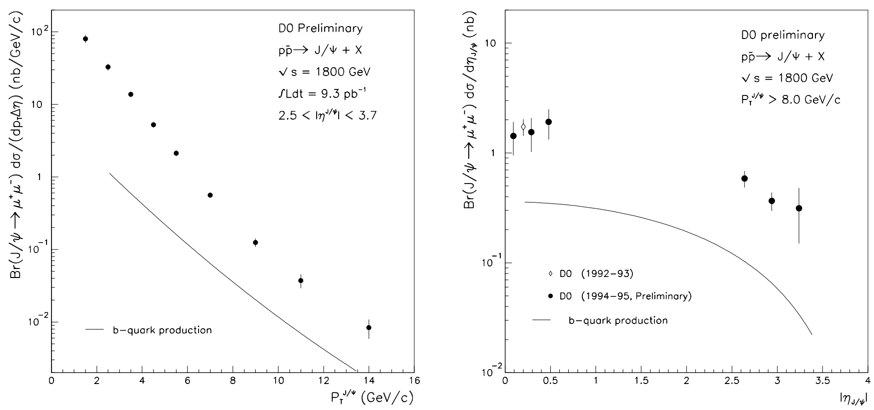

Figure 3: J/ψ differential cross sections: Br$\cdot d\sigma/dp_T$ for $2.5 < |\eta^{J/\psi}| < 3.7$ (left) and Br$\cdot d\sigma/d\eta^{J/\psi}$ (right).

The measurements in the central region are consistent with having no η dependence. However, in the forward region the measured cross section is approximately a factor of 5 lower than in the central region . The data are compared to a preliminary theoretical prediction of the contribution due to b quark decay to J/ψ. It is expected that comparison with a complete theory which includes color octet contributions could be used to check the magnitude of the color octet matrix elements extracted from fits to the central cross section measurements of CDF.

6 Bottomonium Production

The CDF collaboration has published differential cross sections for the Υ(1S), Υ(2S), and Υ(3S) states reconstructed in the $\mu^+\mu^-$ decay channel (see figure 4) based on a data sample of 16 pb^{-1} [8]. The D0 collaboration has measured a combined Υ cross section [9] which is compatible with the CDF result. Recently, theoretical curves which include color-octet contributions were fit to the CDF Υ(1S) and Υ(2S) differential distributions [7]. Figure 4 shows these fit results describe the shape of the p_T distributions well.

Increased statistics using CDF's full 110 pb^{-1} data sample will allow finer binning in p_T, improving the experimental determination of the shape of the Υ p_T distributions. Reconstruction of the χ_b states via Υ(1S)γ decay is currently underway and should provide an additional probe of the underlying Υ(1S) production mechanisms.

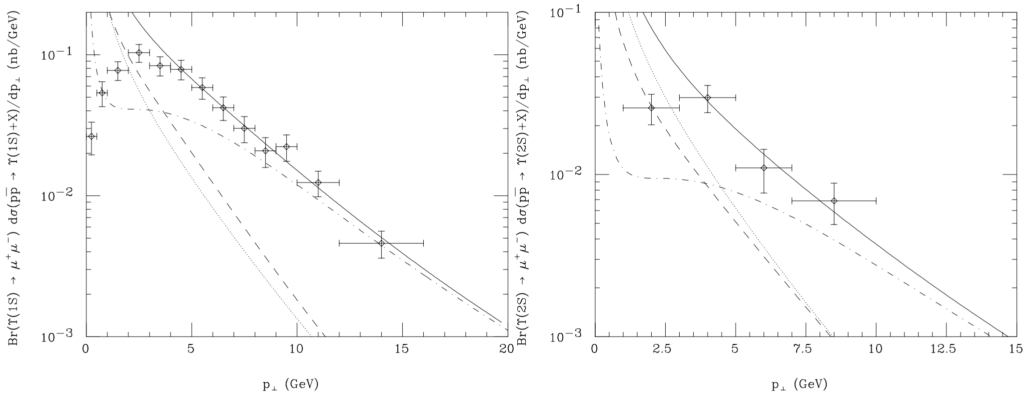

Figure 8 Figure 9

Figure 4: The Υ(1S) (left) and Υ(2S) (right) differential cross sections compared with theoretical predictions. The dotted line shows the color singlet contribution, while the dashed lines are the color octet components fit to the data. The solid line is the sum of all contributions.

7 Summary

Measurements of differential production cross sections for the J/ψ, ψ(2S), and Υ states have been made at the Tevatron Collider. The prompt and b-decay components of both charmonium states have been extracted. The prompt J/ψ cross section has been further subdivided into its direct and χ_c decay components. These measurements have provided the impetus for new theoretical models, such as the color-octet model, which show potential to explain quarkonium production in $p\overline{p}$ collisions. Additional experimental results, such as measurement of the ψ(2S) polarization and the reconstruction of χ_b states currently underway, should provide additional insight into the underlying production mechanisms.

References

[1] F. Abe *et al.*, *Phys. Rev. Lett.* **69**, 3704 (1992)

[2] E. Braaten, S. Fleming, and T. Yuan, OHSTPY-HEP-T-96-001; E. Braaten and S. Fleming, *Phys. Rev. Lett.* **74**, 3327 (1995).

[3] P. Dawson *et al.*, *Nucl. Phys.* B **327**, 49 (1988); M. Mangano *et al.*, *Nucl. Phys.* B **373**, 295 (1992).

[4] S. Abachi *et al.*, *Phys. Lett.* B **370**, 239 (1996).

[5] S. Abachi *et al.*, FNAL-Conf 96/249-E.

[6] E.W.N. Glover, A.D. Martin, and W.J. Stirling, *Z. Phys.* C **38**, 473 (1988).

[7] P. Cho and A. Leibovich, *Phys. Rev.* D **53**, 6203 (1996).

[8] F. Abe *et al.*, *Phys. Rev. Lett.* **75**, 4358 (1995).

[9] S. Abachi *et al.*, EPS HEP Conference, Brussels, Belgium, 27/7 - 2/8, 1995.